Effect of mechanical stresses on the coercive force of the heterophase non-interacting nanoparticles

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Abstract. The theoretical analysis of the effect of uniaxial stress on the magnetization of the system of noninteracting nanoparticles is done by an example of heterophase particles of maghemite, epitaxially coated with cobalt ferrite. It is shown that stretching leads to a decrease in the coercive force H_c, and compression leads to its growth. The residual saturation magnetization I_{rs} of nanoparticles does not change. With increasing of interfacial exchange interaction, coercive force varies nonmonotonically.

Introduction

It is known that the reduction of size of the particle leads to an intensification of reactivity of the magnetic material. As a result, it is natural to assume that small particles are rather heterophase than homogeneous. Moreover, the formation of neighboring magnetic phases can be caused by processes of oxidation or disintegration of the solid solution (see, eg, [1, 2]) occurring in the magnetically ordered grain. Most of the ultrafine magnetic materials of practical interest is two-phase or multiphase single-domain particles. For example, they are carriers of information in the magnetic memory elements, also they are widely used in modern biophysics. Numerous experiments with ultradispersed magnetic materials discovered the dependence of such magnetic properties as coercive force, remanent magnetization and magnetic susceptibility on values and prehistory of the mechanical stresses applied to the samples. The inverse problem is of independent interest: to determine the magnetic prehistory of the sample from its known mechanical properties. This task is extremely important for the magnetic measurements of fatigue of metal constructions, as well as in the study of the paleointensity. Owing to the research based on the dependence of magnetic properties on mechanical stresses, ultradispersed magnets are used, for example, in the sensors of heavy load, in the technology of transformer cores, and control systems of fatigue of metal structures, in electronic article surveillance and many other technical developments.

Model

1. Homogeneously magnetized nanoparticle (phase *1*) of volume V has the form of ellipsoid with elongation[1] q_1, and its long axis oriented along the Oz-axis (see fig. 1).

2. Nanoparticle contains an uniformly magnetized ellipsoidal inclusion (phase *2*) with a volume $v = \varepsilon V$ and elongation of q.

3. The angle between the long axes of the particle and the inclusion is α.

[1] *elongation* — the ratio of the length a of semi-major axis of the ellipsoid to the length b of semi-minor one

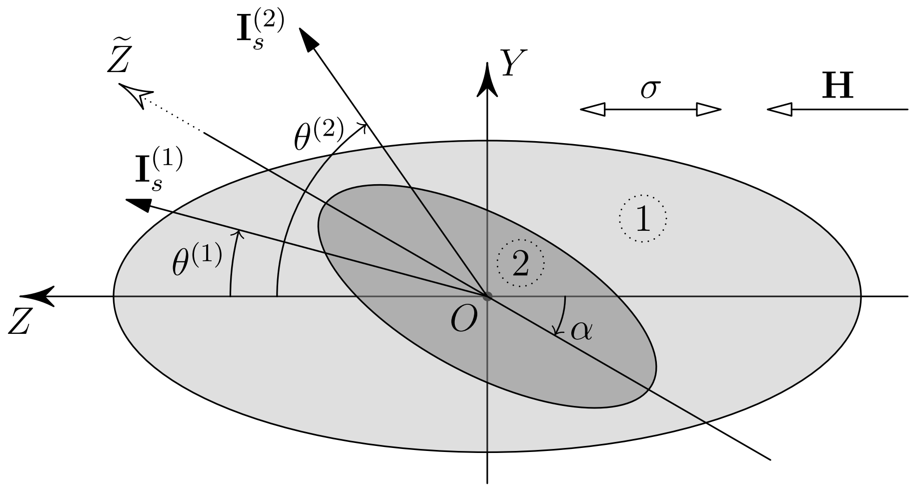

Figure 1: Illustration of the model of two-phase particle

4. It is considered that the axes of crystallographic anisotropy of both uniaxial ferromagnets are parallel to the long axes of the ellipsoids, and the vectors of spontaneous magnetization of phases $\mathbf{I}_s^{(1)}$ and $\mathbf{I}_s^{(2)}$ lie in the plane yOz, that contains the long axes of the magnetic phases, and make angles $\theta^{(1)}$ and $\theta^{(2)}$ with the Oz axis, respectively.

5. Both external magnetic field H and uniaxial mechanical stresses σ are applied along the Oz-axis.

6. The volume of nanoparticles exceeds the volume of superparamagnetic transition.

Results

The calculation of the magnetization, held within the framework of the above mentioned model of two-phase particles — maghemite (γ-Fe_2O_3) epitaxially coated with cobalt ferrite ($CoFe_2O_4$) — is shown in fig. 2. It is easy to see that stretching shifts the magnetization curves to lower magnetic fields H, and the compression leads to the opposite effect. At the same time mechanical stresses do not affect the saturation magnetization, which is determined by the thickness of cobalt coating. These results are determined by the dependence of the critical fields of magnetization reversal on the stresses: stretching decreases the critical fields of magnetization reversal and compression increases it, and the coercivity of the particles changes consequently.

Coercivity H_c depends not only on stress but also on the magnitude of the exchange interaction through the interface A_{in} and on the relative amount of cobalt coating $\tau = 1 - \varepsilon$. When $A_{in} = 0$ or $A_{in} = 3 \times 10^{-8}$ erg/cm coercivity of the particles increases monotonically with an increase in the relative volume of coating, whereas for $A_{in} = -3 \times 10^{-8}$ erg/cm behavior of the H_c is nonmonotonic (see fig. 3).

In addition, a negative exchange interaction leads to a decrease in the coercive force H_c as compared with $A_{in} = 0$, and positive — to its increasing. Features of the dependence of the coercive force of the interfacial exchange interaction A_{in} shown in fig. 4. One can see that the nonmonotonic behavior $H_c = H_c(A)$ is characteristic of nanoparticles with a large ($\tau = 0.9$) or small ($\tau = 0.1$) thickness of the cobalt coating and is being implemented in both positive and negative values of A_{in}.

The nonmonotonic behavior of the coercive force can be explained by considering the ratio of the exchange interaction A_{in} and interfacial magnetostatic interaction A_{ms}. While $A_{in} > A_{ms}$, the

coercivity of the system is determined by the critical field of magnetization reversal from a state with a parallel orientation of the magnetic moments of the phase of nanoparticles to the state in which one phase (conventionally, *the first*) is antiparallel to the external magnetic field H and the other parallel to it. According to [3], this critical field decreases with increasing of A_{in}. When $A_{in} < A_{ms}$, nanoparticles with parallel magnetic moments of the phases remagnetized by switching of the magnetic moment of the first phase into a state parallel to the field H. The critical field of magnetization reversal in this case should increase with increasing of A_{in}.

Noted above nonmonotonic behavior of H_c did not observed in [4, 5], which is obviously associated with a narrower, than in the present study, spectrum of the critical fields of magnetization reversal of two-phase particles. A qualitative comparison of the results with similar calculations presented in [5–7] shows that, just as in these papers, with the growth of phase $CoFe_2O_4$, coercivity increases up to saturation.

References

[1] F. Stacey and S. Banerjee, *The physical principles of rock magnetism*. New-York: Elsevier, 1974.

[2] A. Gapeev and V. Tselmovich, "The microstructure and domain structure of multiphase oxidized titanomagnetites," *Physics of the earth and planetary interiors*, vol. 70, no. 3–4, pp. 243–247, 1992.

[3] L. Afremov, Y. Kirienko, and T. Gnitetskaya, "Influence of mechanical stresses on the magnetic state of dual-phase particles," in *Proceedings of the 8th International Conference Problems of Geocosmos*, (St.-Petersburg), pp. 306–310, 2010.

[4] G. Sawatzky, F. Van Der Woude, and A. Morrish, "Mössbauer study of several ferrimagnetic spinels," *Physical Review*, vol. 187, pp. 747–757, 1969.

[5] J.-S. Yang and C.-R. Chang, "Magnetization curling in elongated heterostructure particles," *Phys. Rev. B*, vol. 49, no. 17, pp. 11877–11885, 1994.

[6] J.-S. Yang and C.-R. Chang, "The influence of interfacial exchange on the coercivity of acicular coated particle," *Journal of Applied Physics*, vol. 69, no. 11, pp. 7756–7761, 1991.

[7] A. Aharoni, "Magnetization buckling in elongated particles of coated iron oxides," *Journal of Applied Physics*, vol. 63, no. 9, pp. 4605–4608, 1988.

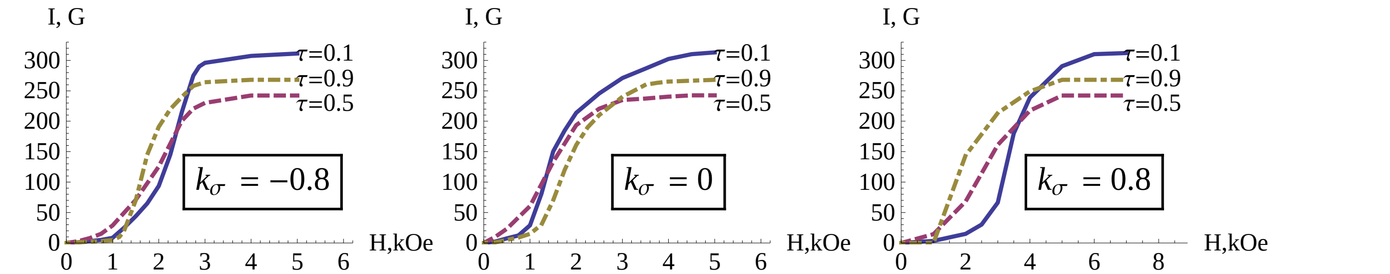

Figure 2: The effect of mechanical stresses $k_\sigma = 3\lambda_{100}\sigma/K_A$ and the relative volume of the cobalt coating $\tau = 1 - \varepsilon$ on the magnetization of elongated nanoparticles (elongation $q_1 = 3$, constant of interfacial exchange interaction $A_{in} = 0$, λ_{100} and K_A are magnetostriction constant and anisotropy constant, respectively)

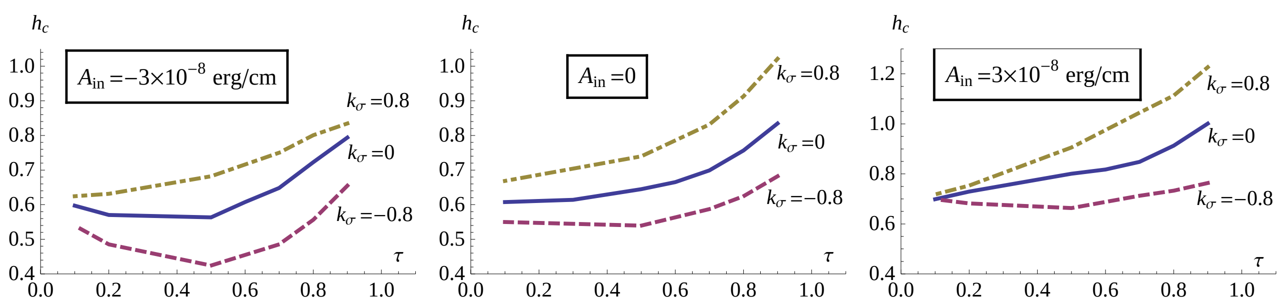

Figure 3: Dependence of the relative coercive force $h_c = H_c/H_{c1}$ of elongated nanoparticles on the relative volume of cobalt coating τ and on the value of the exchange interaction through the interface A_{in} if $q_1 = 3$, $H_{c1} = 2947$ erg

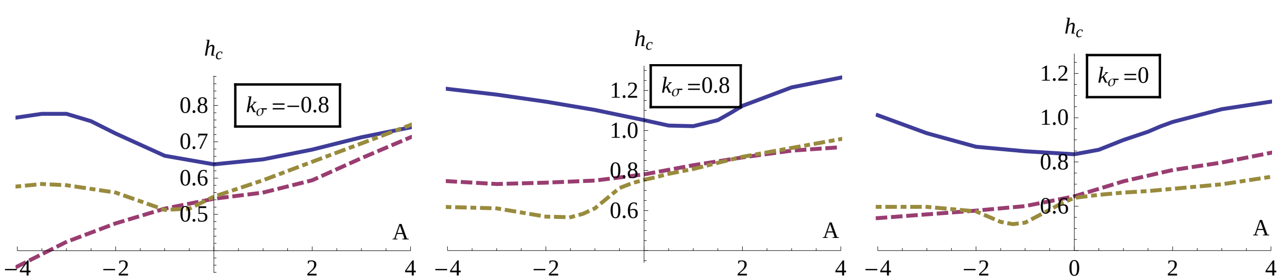

Figure 4: Dependence of the relative coercive force $h_c = H_c/H_{c1}$ of elongated nanoparticles on the value of the exchange interaction through the interface A_{in} and on the relative volume of cobalt coating τ (solid curve corresponds to $\tau = 0.9$, dashed curve — to $\tau = 0.5$, dot-dashed curve — $\tau = 0.1$) if $q_1 = 3$, $H_{c1} = 2947$ erg